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## OBSERVATION OF THE 63μ (O I) EMISSION LINE IN THE ORION AND OMEGA NEBULAE

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ABSTRACT

We report the first observations of the 63μ fine structure transition $p^4 : {}^3P_1 \longrightarrow {}^3P_2$ for neutral atomic oxygen. The measurements were obtained during a series of flights on the NASA Lear Jet at an altitude of ~ 13.7 km. In the Orion Nebula (M42) our observed line strength is $8 \times 10^{-15}$ watt $cm^{-2}$ which we estimate to be ~ 0.3 o/o of the energy radiated at all wavelengths. For the Omega Nebula (M17) the line strength is $2.4 \times 10^{-15}$ watt $cm^{-2}$, and the fraction of the total radiated power is slightly higher. These figures refer to a 4' x 6' field of view centered on the peak far infrared emission from each source. The uncertainty in the line strength is ~ 50% and is caused by variable water vapor absorption along the flight path of the airplane. Our estimate of the line position is 63.2μ (+0.1, -0.2)μ. The prime uncertainty is due to the uncertain position of the (O I) emitting regions in our field of view.

Introduction.

During the past few years far infrared observations at moderate spectral resolution have led to the discovery of a number of emission lines from multiply ionized atoms in the interstellar medium (Ward et al, 1975, Baluteau et al, 1976, Dain et al, 1978, Melnick et al, 1978). The radiating ions are collisionally excited by the surrounding plasma and then return to a lower excited state through radiative fine structure transitions.

The present letter reports on the observation of 63μ neutral oxygen emission from the Orion and Omega Nebulae. The 63μ (OI) line is particularly interesting because it provides information about an intermediate interstellar temperature regime. The temperature, T, for which kT equals the threshold energy for collisional excitation of the $^3P_1$ state is 228°K. Below this temperature collisional excitation still is possible since the excitation rate is roughly proportional to $T^{1/2}$ exp (-228/T) (Dalgarno and McCray, 1972), but the excitation is appreciably attenuated at temperatures below ~ 100°K. The temperature also is likely to be below 6000°K where the optical transitions around ($\lambda$6300) (see fig. 1) start to provide dominant cooling. (The optically observed line strength must, however, be interpreted with care if we wish to set limits on the temperature of the region which radiates at 63μ. Dust absorption within the emitting region or along the line of sight can appreciably lower the ($\lambda$6300) flux the observer receives.)

The 63μ radiation then appears to come not from within the H II regions but either from the peripheral CII/SII regions-- carbon and sulfur respectively are ionized by radiation at 11.3 and 10.4 ev--or from shocks generated in the surrounding neutral clouds. For the Orion Nebula, Wurm and Rosino (1959, 1965) and Gull (1978) have obtained extensive sets of photographs taken through narrow band filters. Effectively these present monochromatic pictures of the Nebula seen through individual spectral lines. Gull notes that the (OI) (λ6300 Å) emission line (Fig. 1) is nearly as bright in the bar-like structure to the south east of θ1 Orionis as in the brightest central part of the Nebula. Becklin et al (1976) have detected infrared emission from this bar and consider it to be an ionization front--a region beyond which singly ionized carbon and sulfur might be expected. Gull in fact does find strong (SII) emission from the bar and in general remarkable similarity between the appearance of pictures obtained at (λ6300 Å) and with a filter at (λ6725 Å) where the (SII) (λ6717 Å) and (λ6731 Å) emission lines are seen. Abundance ratios of (OII)/(OIII) and (OI)/(OII) according to Gull also increase across the bar as we move away from θ1 Orionis. Other structures observed in (OI) and (SII) emission include a number of condensations noted by Gull et al (1973) and earlier by Wurm and Rosino (1957). Hill and Hollenbach (1978) have recently discussed the effects of expanding HII regions on neutral surrounding gas clouds, and in particular have estimated the cooling of ionized carbon regions and shocked domains through (OI) 63μ emission, through the rotational transitions of $H_2$ and through rotational transitions of CO. It appears that emission through the 63μ transition may be providing one of the chief cooling mechanisms by means of which CII and shocked regions radiate energy. The estimates of the 63μ line strength Hill and Hollenbach present in fact suggested to us that a search for this line might prove successful.

Observations.

Observations were undertaken with equipment and procedures identical to those described in previous Letters (Dain et al, 1978, Melnick et al, 1978). Our observations were carried out from the NASA Lear Jet flying at an altitude of approximately 13.7 km. Our liquid helium cooled grating spectrometer was mounted on the 30 cm telescope. Our chopping frequency was 25 Hz and the chopper throw 16'. The instrumental resolving power was ~ 150 for sources small compared to the 6' x 4' field of view, and the system noise equivalent power was ~ $9 \times 10^{-13}$ watt $Hz^{-1/2}$ including all losses due to the chopper, the telescope and atmospheric effects.

We observed the Orion Nebula and M17 each on two nights and obtained calibration curves for the same spectral regions by making observations of Mars and Venus. Both of these planets had virtually identical spectral shapes in the region of interest. We chose to use Venus, the brighter of the two sources, as our primary calibrator.

The prime reason for calibrating the spectra is to remove the effects of telluric water vapor. Atmospheric (OI) absorption at 63μ is not expected to play a major role since the absorption line is so narrow that the source Doppler shift removes the astronomical 63μ emission line well clear of the atmospheric feature.

The final source spectra compensated for atmospheric absorption are shown in Fig. 2. The best estimate for the

$^3P_1 \longrightarrow {}^3P_2$ transition wavelength is 63.2μ. This should be compared to the expected line position, 63.14μ, obtained from the visual transitions at wavelengths (λ6300.3) and (λ6363.8) shown in Fig. 1 (cf Osterbrock, 1974). The possible error on the long wavelength side is $\lesssim$ 0.1μ. At longer wavelengths the line would be absorbed by the atmosphere's 63.3μ feature (Fig. 3), and we observe no change in the line strength on individual passes through the spectrum taken at slant paths ranging from 2 to 4 air masses in the course of a flight. On the short wavelength side of the spectrum the error in the line position could be up to 0.2μ. Here the main uncertainty is our lack of information on the source location within the field of view.

To understand this we must describe the procedure for finding the source during flight. Once the correct star field is identified, the telescope is pointed in roughly the correct direction and the field is scanned to orient the telescope along the direction in which the signal peaks. For Orion the dominant source in the far infrared is the Kleinmann-Low Nebula. We therefore centered this Nebula in our field of view before starting the spectral scans. If the source of (OI) 63μ emission then lies at a point imaged near one edge of the slit, its wavelength may be registered as longer or shorter than the actual wavelength by as much as 0.2μ; and this constitutes our main source of uncertainty in the line position. Similarly our main uncertainty about the line strength is related to the line position and depends on the proximity of the 63μ line to atmospheric water vapor absorption features.

The 63μ line widths we register are wider than a series of (OIII) 51.8μ emission lines we observed in the same series of flights. This is suggestive of a distributed emitting region whose image extends across the entrance slit.

Discussion.

The 63μ flux we detect is extraordinarily bright. In M42 at 0.5Kpc, it amounts to ~$600L_\odot$, in M17, at 2Kpc, to ~$2900L_\odot$ in the line.

In order to estimate the minimum temperature of the region we may assume that the emitting region filled our entire field of view $\Delta\Omega$; that the brightness temperature in the line was T; that the line width was the Doppler width $\Delta\lambda_D$; and that the region was opaque within this width. Then the received radiation would be

$$B(\lambda,T)\ \Delta\lambda_D\ \Delta\lambda,$$

where $B(\lambda,T)$ is the blackbody function. Taking the full Doppler width to be $\sim(\lambda/c)\ (1.4kT/m_0)^{1/2}$, where $m_0$ is the mass of an oxygen atom, it is easy to show that the temperature in our 24 square minute field of view would have to be T ~650°K to account for the observed brightness in Orion. At this temperature the Doppler width amounts to a velocity of 0.7 km $sec^{-1}$. This temperature could drop somewhat if the oxygen occupied a regime in which turbulent velocities or a velocity gradient existed along the line of sight. To be effective in appreciably lowering the required temperature, the velocity spread would have to amount to several kilometers per second. For Orion a velocity spread amounting to 10 km $sec^{-1}$ along the line of sight would permit a temperature as low as 115°K. On the other hand if there is any correlation between the distribution of oxygen giving rise to the visible and the infrared radiation, then the small fraction of the field of view occupied by the oxygen again would require an increased temperature. We may therefore guess that the emitting region has a temperature of at least a few hundred degrees Kelvin. A very coarse upper limit may be set for the temperature of the emitting region:

Johnson (1968) provides estimates of the strengths of various visual lines in the spectrum of Orion and relates them to the strength of H $\beta$. He estimates the ($\lambda$6300) line to be about 6.5% as strong and the ($\lambda$6363.8) line to be 1.6% as strong as H $\beta$ --which Boyce estimates as providing a flux of $7.1 \times 10^{-8}$ erg $cm^{-2}$ $sec^{-1}$ at Earth. The combined strength of the two visual oxygen lines therefore is a factor of 14 lower than the observed 63$\mu$ line strength. Even if the absorption of the two visual lines amounts to one magnitude between source and observer, the 63μ line still is a factor of 5.5 brighter than the visual line. This suggests a temperature below ~3800°K for the radiating region if we take electron collisions to be primarily responsible for the line excitation. This conclusion must, however, be treated with some caution. We do not know whether electron, proton or atomic collisions provide the main excitation mechanism; we are uncertain about the collisional deexcitation that affects the 63μ line strength; and we are not sure whether the regions from which the visual lines originate coincide with the source of 63μ radiation. However, if we take the temperature of the emitting region to lie between several hundred degrees and ~4000°K, we see that it appears to be distinct from the H II regions with their characteristic temperature of 7000°K, as well as from the standard H I clouds at temperatures below 100°K. Instead we seem to be detecting a neutral region at intermediate temperature.

Although our observed line strength is strong, five or six orders of magnitude stronger than the 2.6 mm CO line strength in our fields of view in M17 and M42 (Lada et al, 1974, Kutner et al, 1976), we must remember that the transitions between high lying levels of CO, and a 156μ transition due to singly ionized carbon may also be strong and may be effective in competing with the 63μ transition.

The cooling of a gas by collisionally excited oxygen atoms has been described by Dalgarno and McCray (1972). Collisions with atoms dominate in regions of low electron density. Dalgarno and McCray give the cooling rate per unit volume as $n_H n_O L_H(T)$ where $n_H$ and $n_O$ respectively represent the hydrogen and neutral oxygen atomic densities, and $L_H(T)$ is the cooling efficiency for collisions with neutral hydrogen. The total flux emitted at the surface of an optically thin nebula with dimension d along the line sight then becomes $B=1/2\ n_H n_0 L_H d$. For the Orion Nebula our observations correspond to a minimum value $1/2\ n_H n_0 L_H d \gtrsim 1.3 \times 10^{-1}$ erg cm$^{-2}$ sec$^{-1}$ at the surface of the nebula, provided we assume that radiation reaches our detectors uniformily from the entire field of view. Hill and Hollenbach specifically have computed the observable 63μ radiation for shocked neutral gas regions and CII domains, and from the D - type ionization fronts in which a shock precedes the ionization front. The highest predicted emission in their models comes from a region in which the initial neutral hydrogen density is $n_H \sim 10^4$ cm$^{-3}$, and the gas becomes compressed by a factor of 30 by a shock moving through the neutral gas at 11.8 km sec$^{-1}$. The expected 63μ line emission then is $5 \times 10^{-2}$ erg cm$^{-2}$ sec$^{-1}$ which is a factor of 2.5 below the minimum observed value we cite above.

For CII regions Hill and Hollenbach give a surface brightness estimated as

$$B(63\mu) \simeq 1.2 \times 10^{-21}\, Ne^{-228/T}\ \mathrm{erg\ cm^{-2}\ sec^{-1}}$$
$$\text{if } n_H \gtrsim 4 \times 10^5\ \mathrm{cm^{-3}},$$

$$B(63\mu) \sim 3 \times 10^{-27}\, n_H N e^{-228/T}\ \mathrm{erg\ cm^{-2}\ sec^{-1}}$$
$$\text{if } n_H \lesssim 4 \times 10^5\ \mathrm{cm^{-3}}.$$

Here N is the column density of hydrogen atoms along the line of sight, and the oxygen abundance is taken to be $6.8 \times 10^{-4}$. If we assume that the temperature of the gas in Orion is ~115°K, the lowest our previously cited figures permit, then our observed brightness would require a column density $N \sim 10^{21}$ cm$^{-2}$ for the case where $n_H \sim 4 \times 10^5$ cm$^{-3}$ in the CII region. This would require our looking to a depth of $2.5 \times 10^{15}$cm at that density. These densities are not unreasonable in the post-shock gas. In this shocked gas we also might expect to find the velocity gradient required to keep the gas temperature low and still provide the 63μ line intensity observed. At the distance of the Orion Nebula the corresponding mass of the radiating region is $\sim 10^{34}$g.

If the temperature is permitted to rise, exp-(228/T) approaches unity and the required column density and mass can drop by a factor of up to ~7. In a region that has been radiatively dissociated as well as shocked, the gas temperature can easily be high enough to provide these conditions. This mass estimate in no way depends on the ionization of carbon and would hold equally well for any gas at the given temperatures. Collapsing protostellar aggregates might therefore radiate at this wavelength as well.

In any case it is only possible here to show that conditions not too different from those permitted by some current models appear to provide fluxes which, though high, agree in order of magnitude with those we observe. We will, however, need to further our understanding by undertaking observations at higher spatial resolution in order to tell the sizes of the regions that emit the 63μ radiation.

Other measurements of similar importance would include 63μ observations of regions known to be strong in CII or $H_2$ emission to check for correlations with the emission strengths obtained from these domains. $H_2$ emitting regions have been assumed to be shocked regions, and as discussed above, the CII domains are likely candidates for (OI) emission. If sufficiently high spatial resolution cannot be obtained to tell us which type of region emits strongly at 63μ, perhaps lower resolution studies in which a larger number of astronomical sources are compared for possible correlations of (OI), CII recombination lines, and $H_2$ emission line radiation, would be worthwhile.

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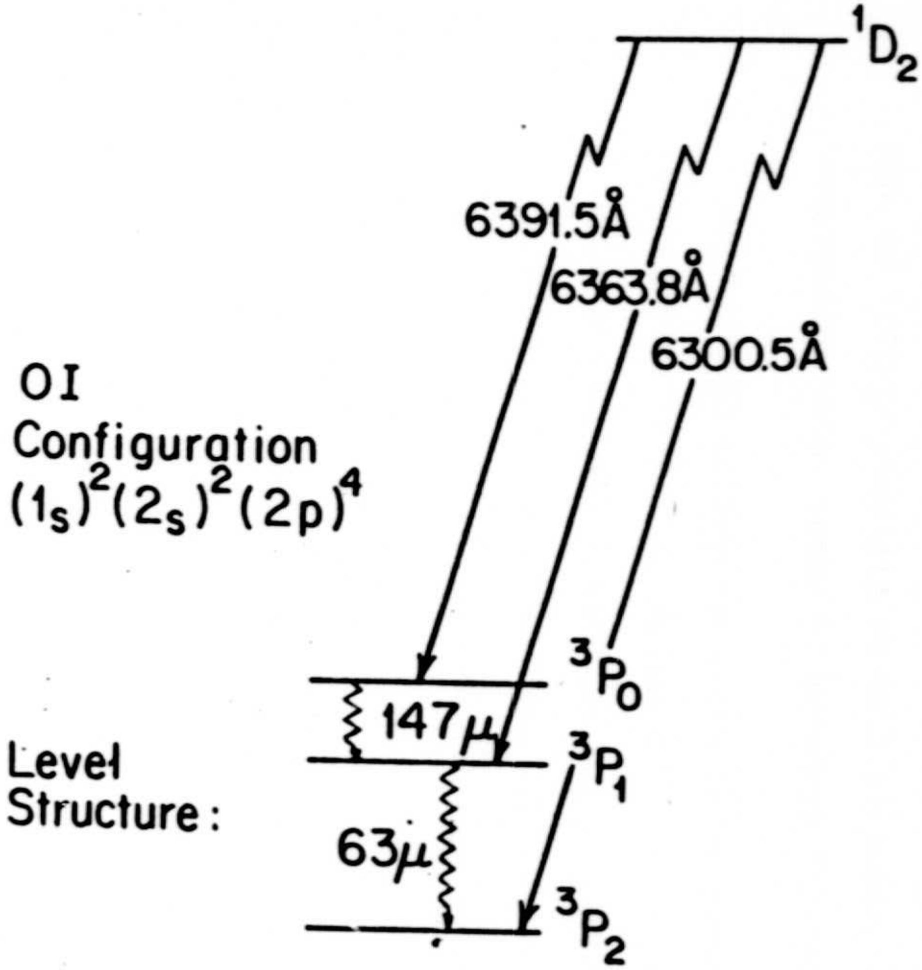
FIGURE CAPTIONS

Fig. 1. Level diagram for the lower energy states of neutral oxygen atoms.

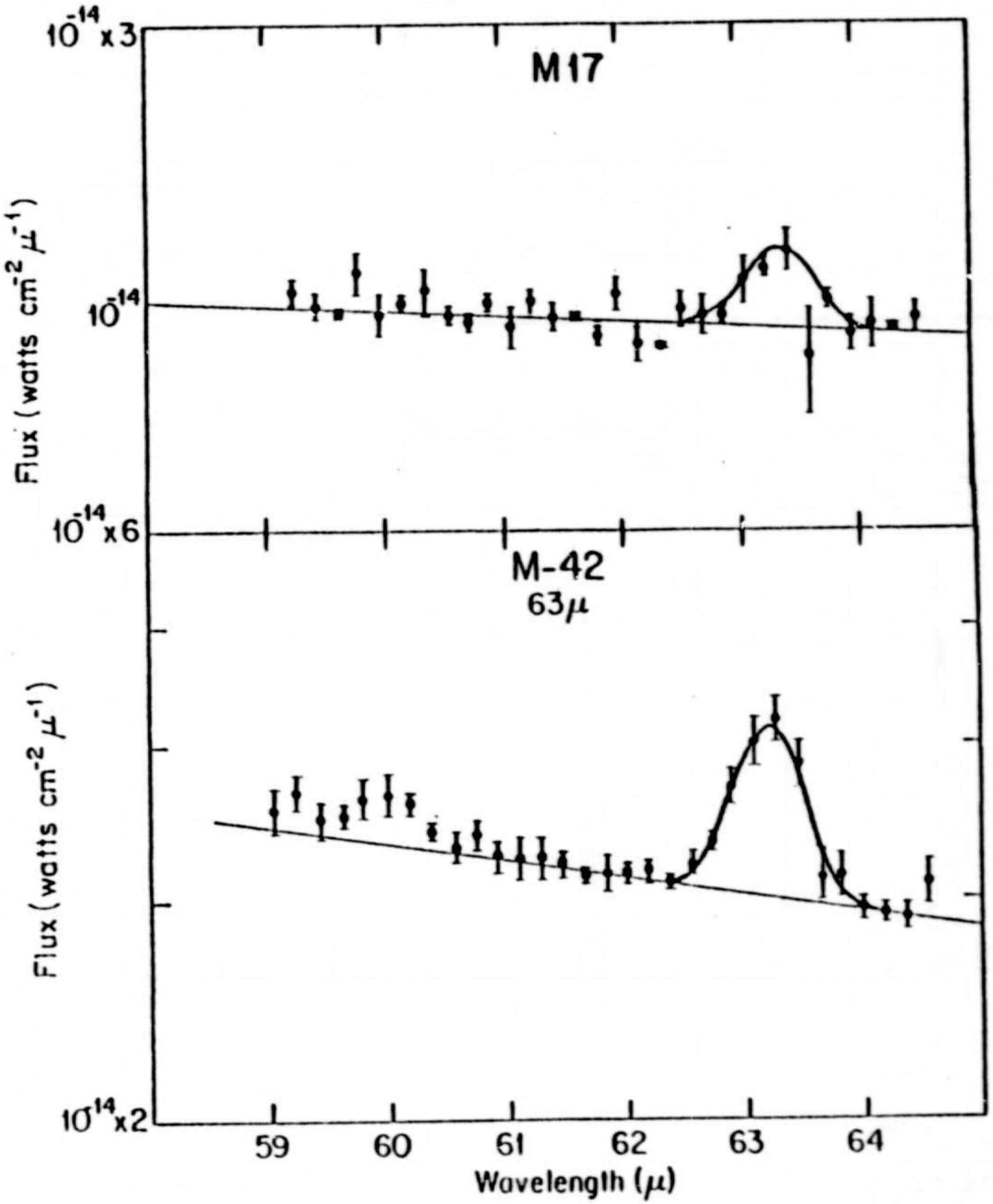
Fig. 2. 63μ emission lines in M17 (top curve) and M42 (bottom) observed from an altitude of 13.7 km and corrected for atmospheric water vapor absorption.

Fig. 3. Atmospheric water vapor absorption features as obtained from Traub and Stier (1975) showing the measured (OI) line position. The grating step size and spectral resolution of our grating instrument also are shown.



$^1D_2$
6391.5Å
6363.8Å
6300.5Å
OI
Configuration
$(1_s)^2(2_s)^2(2p)^4$
$^3P_0$
147μ
$^3P_1$
Level
Structure:
63μ
$^3P_2$

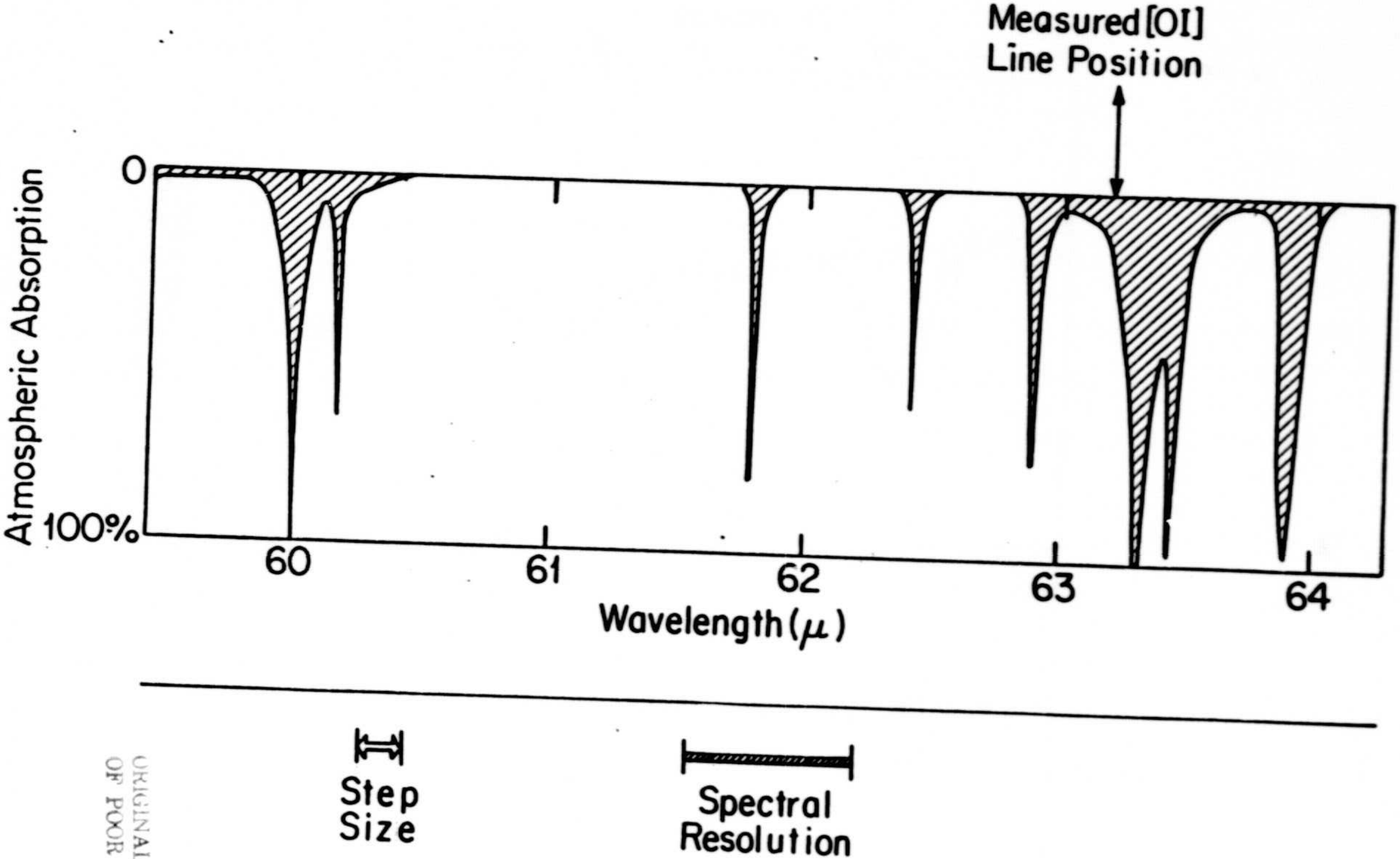

Figure 1



M17
M-42
63μ
10^-14 x3
10^-14
10^-14 x6
10^14 x2
Flux (watts cm^-2 μ^-1)
59
60
61
62
63
64
Wavelength (μ)




Figure 2



Measured [OI]
Line Position
Atmospheric Absorption
0
100%
60
61
62
63
64
Wavelength (μ)
Step
Size
Spectral
Resolution


Figure 3